Optimizing Energy Management Strategy and Degree of Hybridization for a Hydrogen Fuel Cell SUV

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Questions to be answered by this study:

- What optimization algorithms work well for hybrids (which are 'SOC-noisy')?
- Is having batteries beneficial for an H_2 fuel cell, and if so what sizes of components are optimum?
- How sensitive is optimal fuel cell vehicle design to the drive cycle used?

Outline

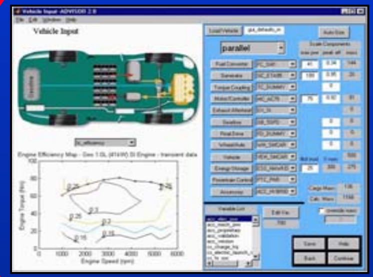
- Who are we?
- What is ADVISOR?
- Optimization algorithms investigated
- How optimization is linked to ADVISOR
- Previous work in this area
- Problem definition
- Results
- Conclusions
- Future Work

National Renewable Energy Laboratory (NREL)

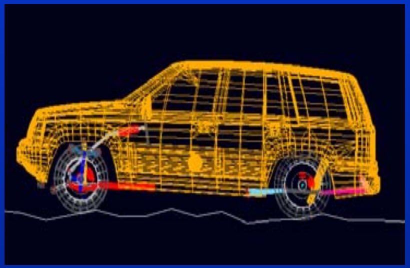
- NREL Mission
  - Lead the nation toward a sustainable energy future by developing renewable energy technologies, improving energy efficiency, advancing related science and engineering, and facilitating commercialization
- Established in 1977 as Solar Energy Research Institute (Achieved National Laboratory status in 1992)
- One of eleven DOE National Laboratories
- Current staff of approximately 780
- Estimated operating budget of $188M for FY00
- Located in Golden, Colorado, USA (15 miles west of Denver)

Hybrid Electric Vehicle Program at NREL Involves 3 Main Areas of Emphasis

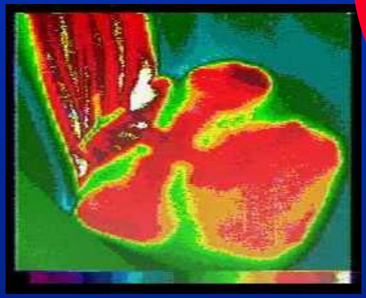
ADVISOR



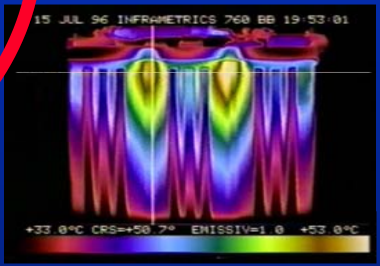
Digital Functional Vehicle



Vehicle Systems Analysis



Vehicle Auxiliary Load Reduction



Battery Thermal Management

US Big 3 Partnership
HV program: 55 mpg
PNGV: 80 mpg goal

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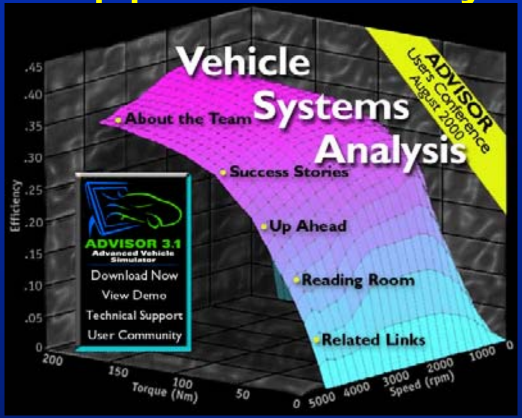
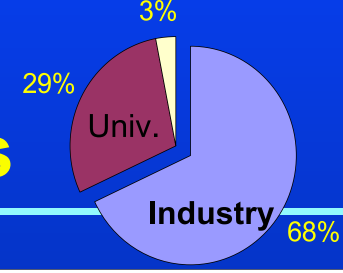
Background on ADVISOR

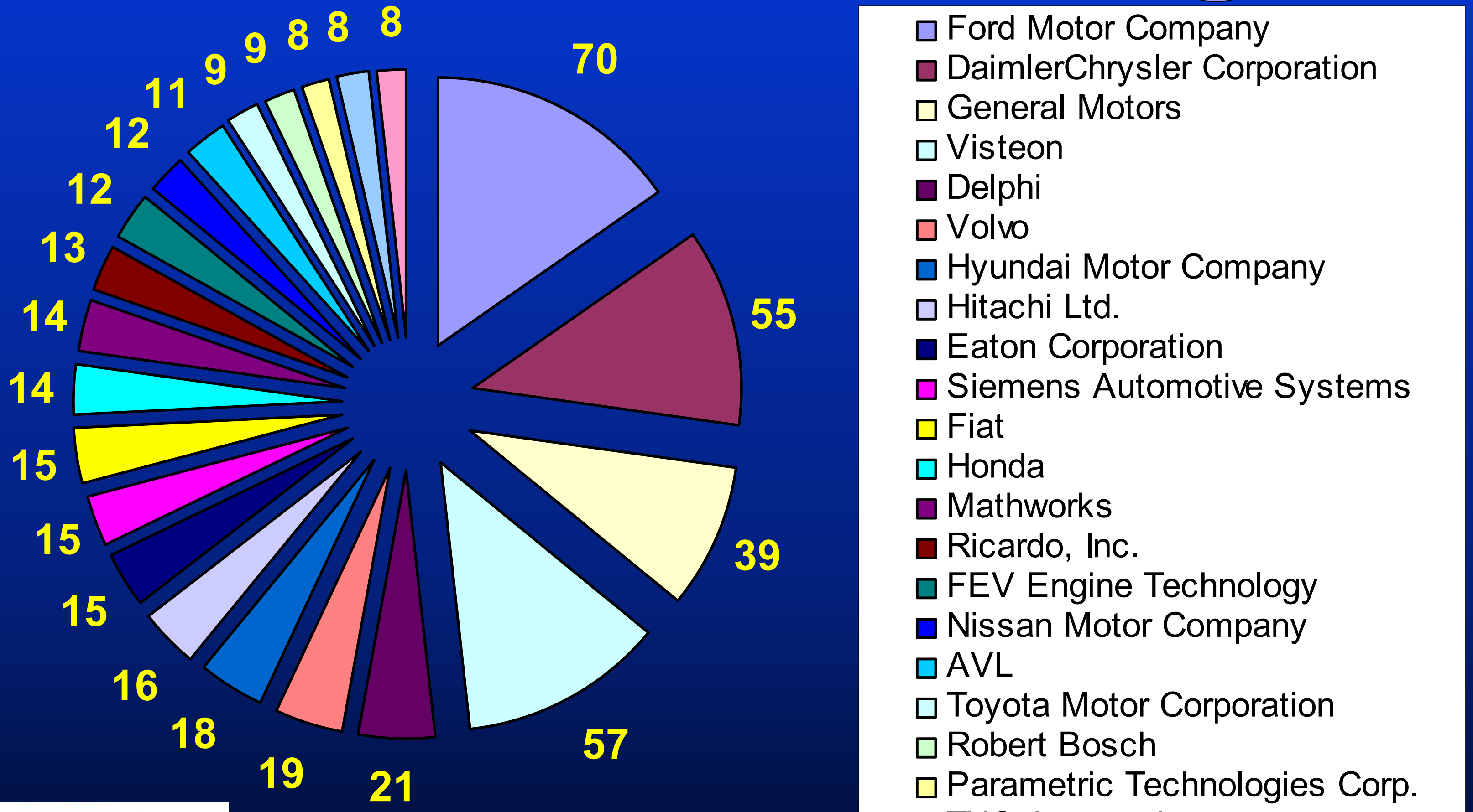
- ADVISOR = ADvanced VehIcle SimulatOR
  - simulates conventional, electric, or hybrid vehicles (series, parallel, or fuel cell)
- ADVISOR was created in 1994 to support DOE Hybrid Program at NREL
- Released on vehicle systems analysis web site for free download in September, 1998 (www.nrel.gov/transportation/analysis)

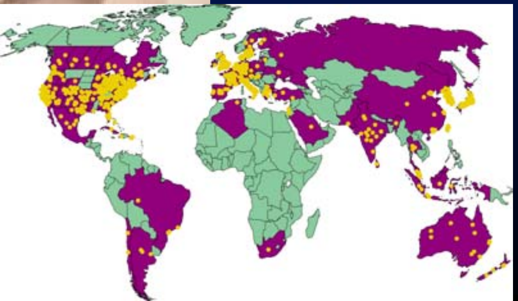


- Downloaded by over 3800 people around world
- Users help provide component data and validation, feedback for future development
- Have held 2 User Conferences in last two years

2/3 of Users are from Industry, All Major Auto OEMs & Suppliers





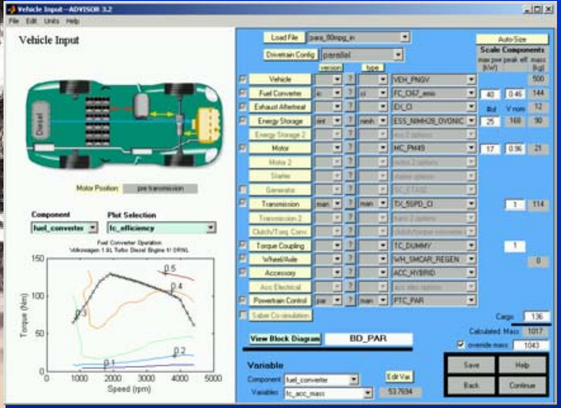


Legend includes organizations with 8 or more users since v2.0

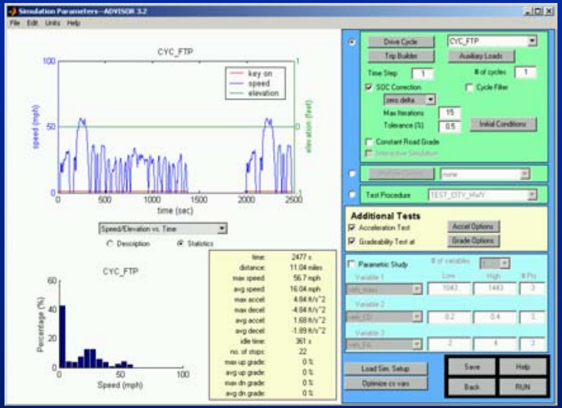
As of 9/4/01

Three Main ADVISOR GUI Screens – ‘GUI-Free’ version Used for Optimization

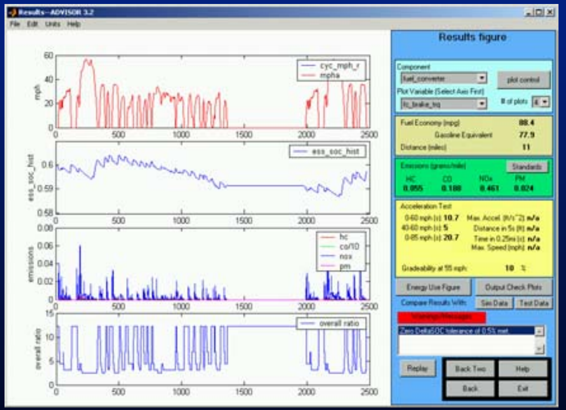
Vehicle Input



Simulation Setup



Results



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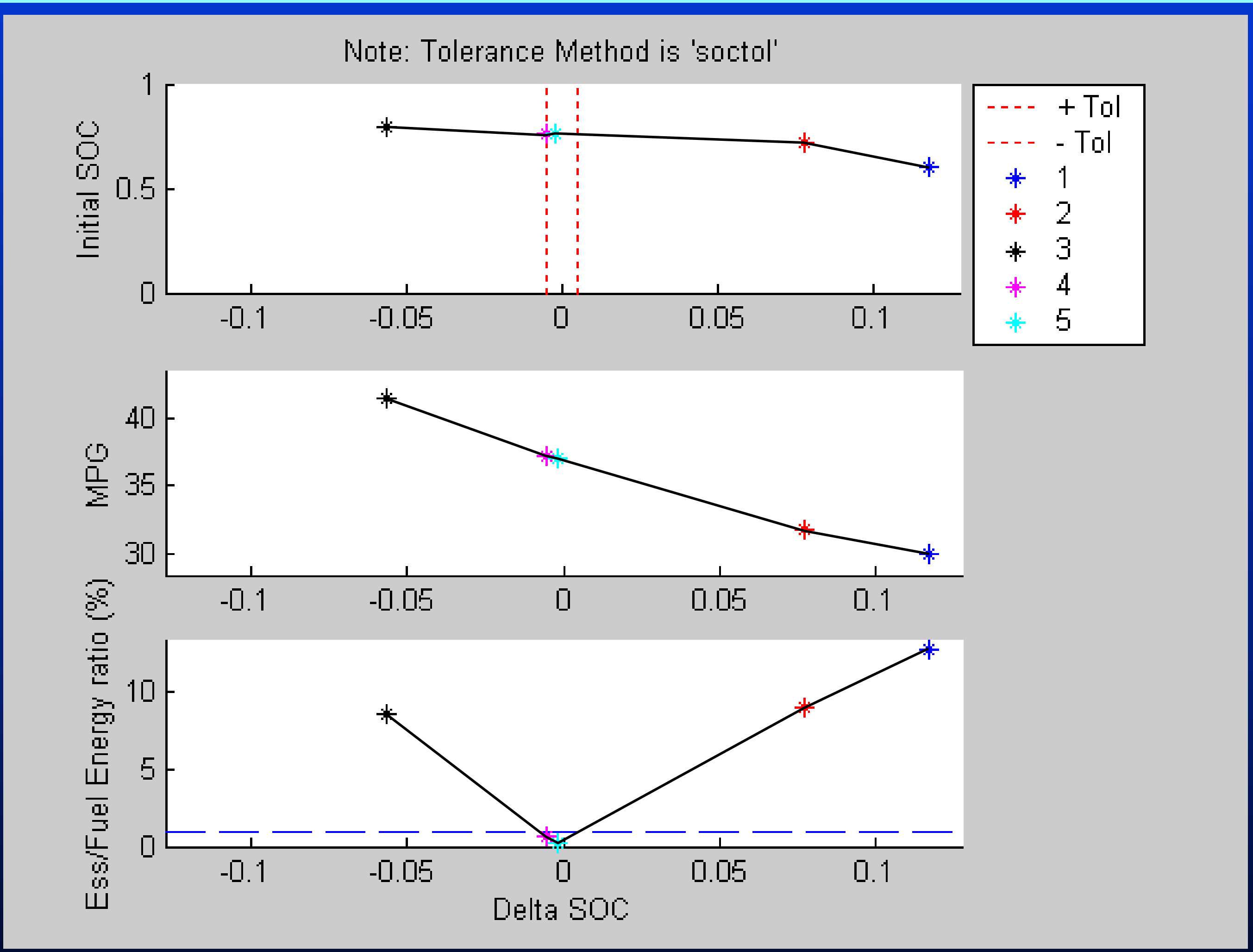
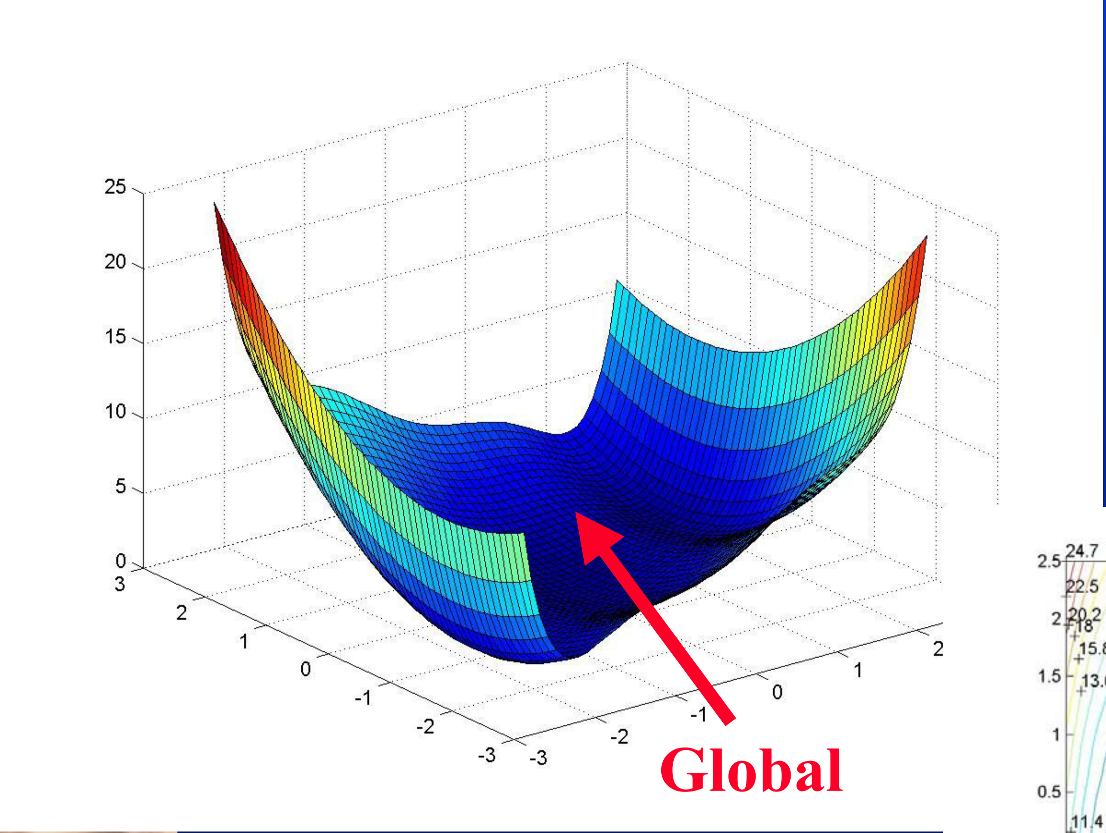
SOC Balancing Over a Drive Cycle Can Result in Response "Noise"

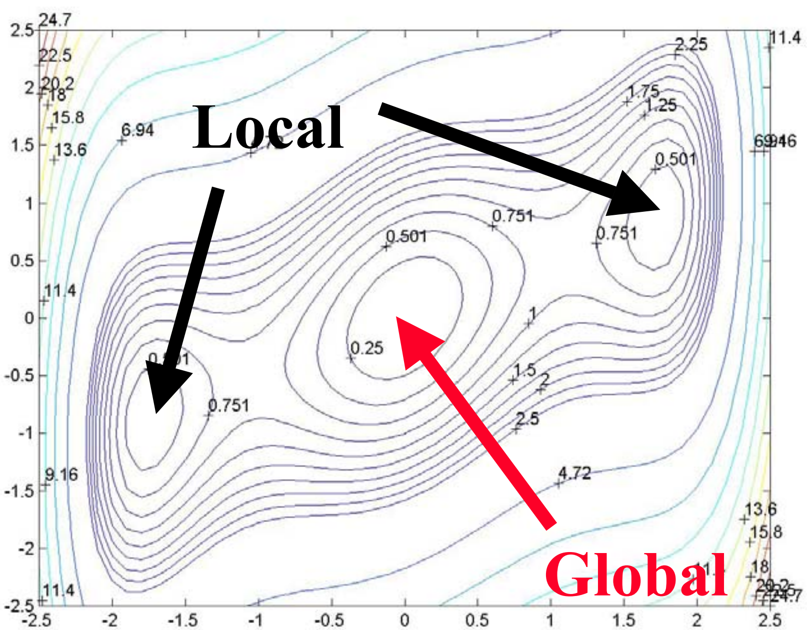


2D Sample Problem –

3-Hump Camel Back with 2 Local, 1 Global Minimum

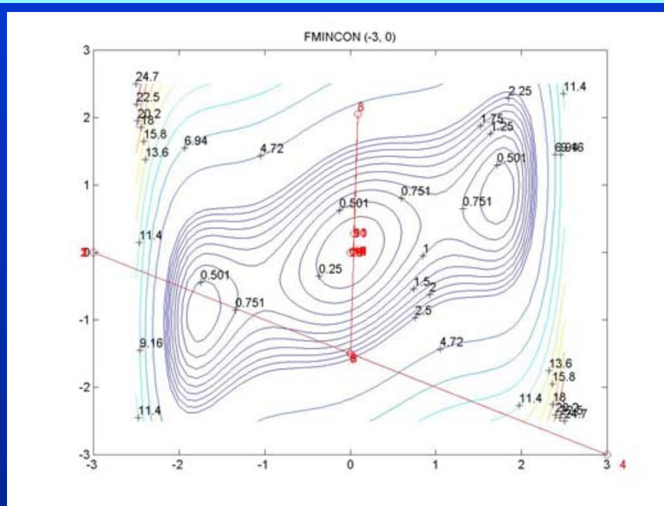


Sample chosen because small potholes resemble design space for HEVs with SOC balancing 'noise'

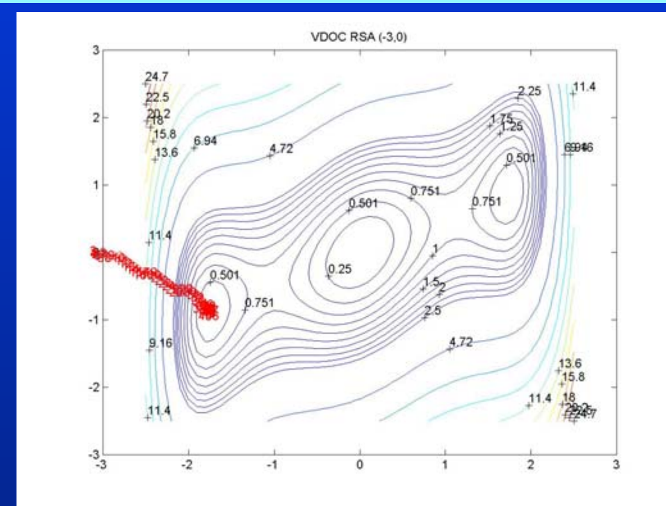


Comparison of 4 Algorithms Investigated

Starting point at –3,0 (left, middle)

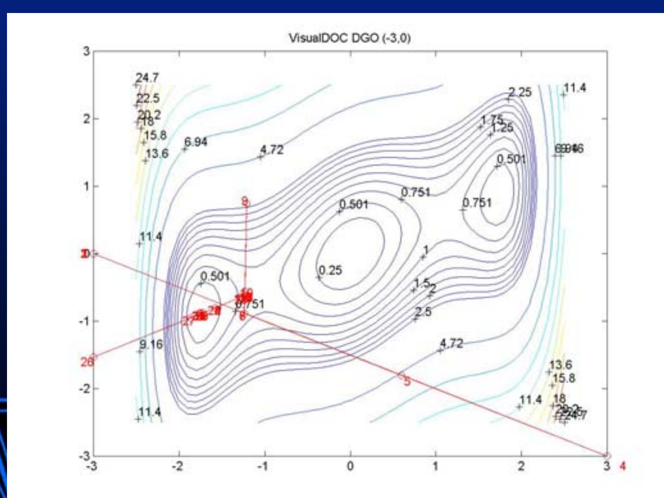


MATLAB FMINCON

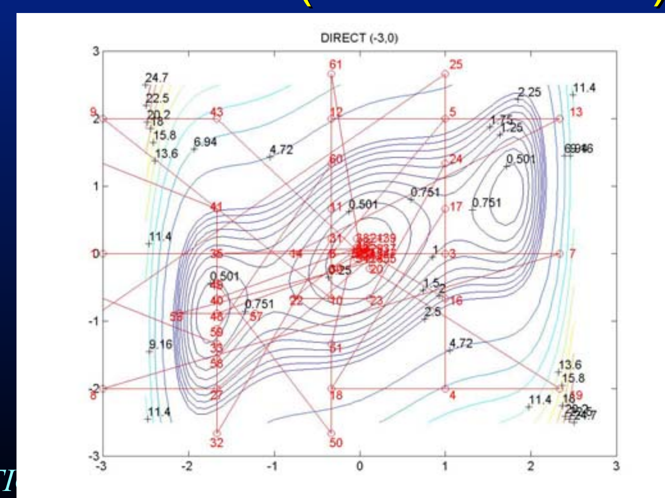


VisualDOC RSA

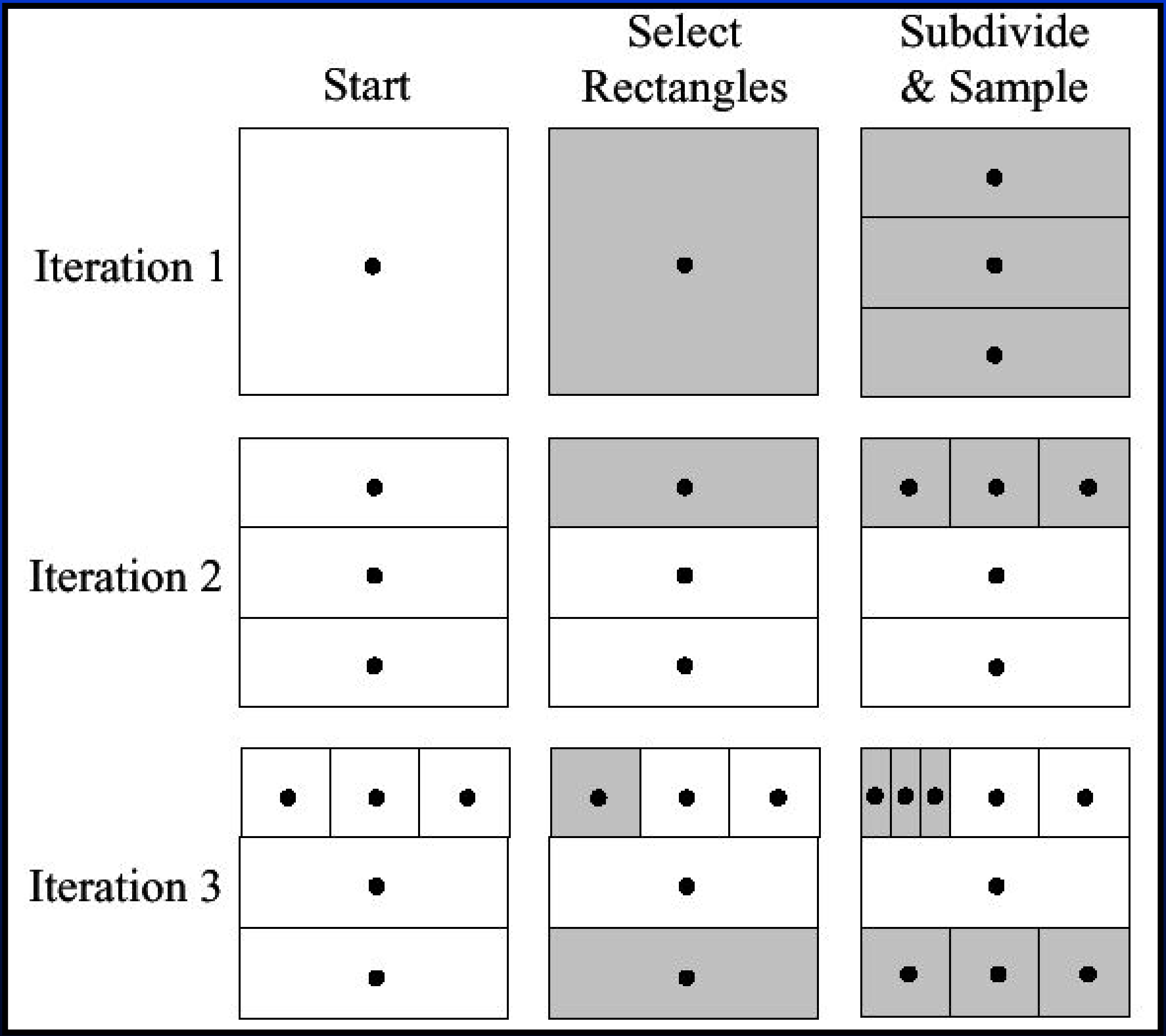
VisualDOC DGO



DIRECT (derivative-free)



Design Point Selection Process in DIRECT



Encyclopedia of Optimization, Kluwer Academic Publishers. June,1999.

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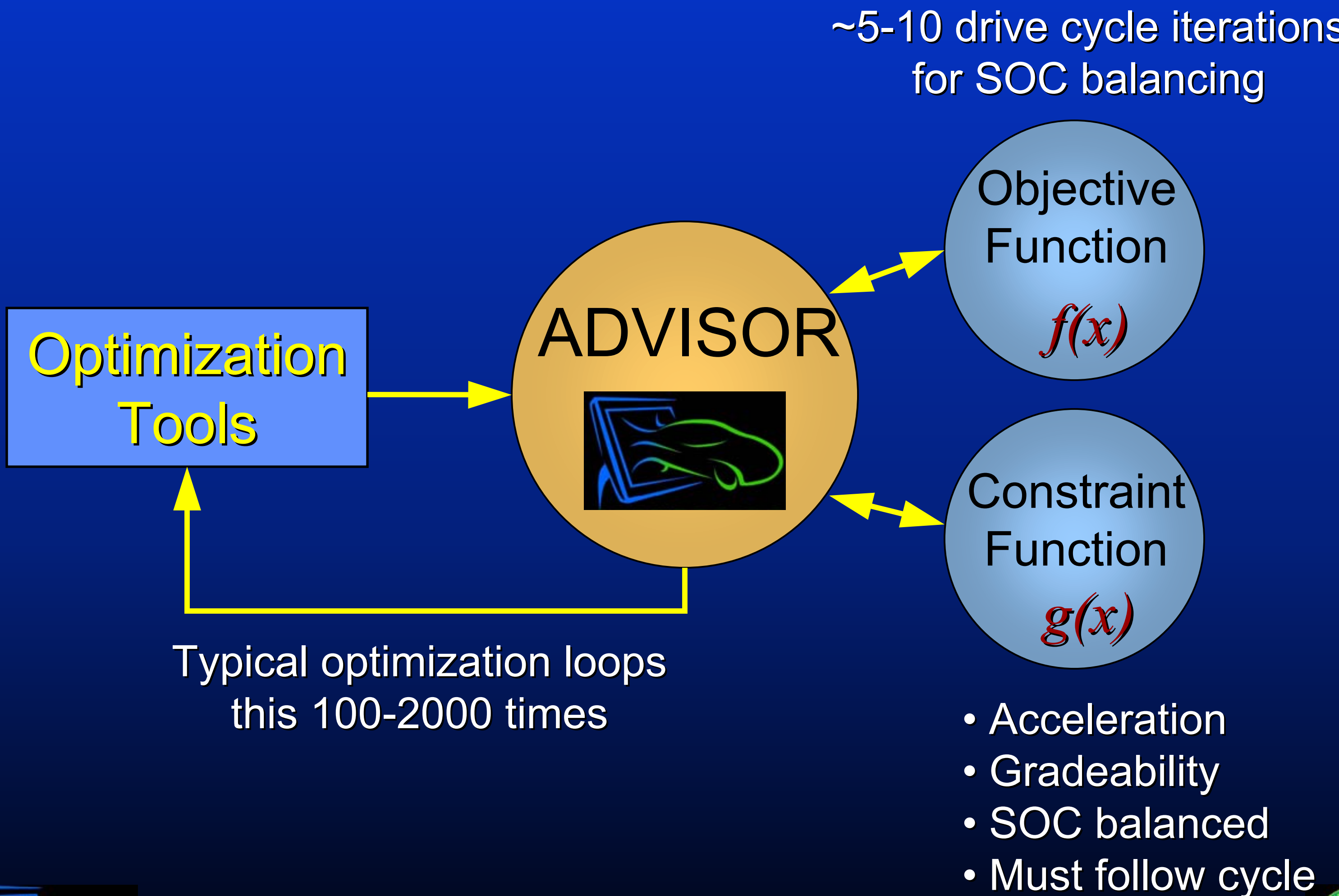
Using ADVISOR in an Optimization Loop as both the Function Call and Constraint Evaluation



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Previous Work in This Area

- David Friedman (University of California, Davis) study results (1999)
  - Is hybridization necessary for a direct hydrogen fuel cell vehicle?
    - Concluded that this is dependent on drive cycle and ability to capture regenerative braking energy
- Parametric Analysis with Virginia Tech. (2001)
  - Varied fuel cell and battery power characteristics and quantified impacts on several drive cycles
    - Again it was shown that hybridization is beneficial to improve vehicle fuel economy

FutureTruck

Fuel Cell vs. Battery Size Trade-off Study
(Previous work with Virginia Tech.)

- Study showed that a ratio of fuel cell power to total power of 0.25-0.3 provided the best city/highway composite fuel economy

- Based on
  - Energy Partners fuel cell data
  - Hawker Genesis lead acid batteries
  - GE AC induction traction motors

2001-01-0236

Degree of Hybridization Modeling of a Fuel Cell Hybrid Electric Sport Utility Vehicle

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Virginia Polytechnic Institute and State University, Blacksburg, VA

Keith B. Wipke
National Renewable Energy Laboratory, Golden, CO

ABSTRACT

An ADVISOR model of a four-wheel drive large sport utility vehicle with a fuel cell / battery hybrid electric drivetrain is developed using validated component models. The vehicle mass, electric traction drive, and total net power available from fuel cells plus batteries are held fixed. Results are presented for a range of fuel cell size from zero (pure battery EV) up to a pure fuel cell vehicle (no battery storage). The fuel economy results show that some degree of hybridization is beneficial, and that there is a complex interaction between the drive cycle dynamics, component efficiencies, and the control strategy.

INTRODUCTION

The main benefit of hybridization in a vehicle with an internal combustion engine is load leveling to improve the overall efficiency of the engine operating region. A fuel cell stack generally has relatively high efficiency at very light load, and a fuel cell system may also have good part load efficiency depending on the system parasitic loads (primarily air compressor power). This part load efficiency makes fuel cells attractive for light duty vehicle loads, and would seem to eliminate the need for hybridization. But the start-up of a fuel cell system, including bootstrapping a high-voltage air compressor drive, and cold-start transient response power limitations, may require hybridization. While neither of these important issues are specifically addressed in the current work, the energy efficiency may still be improved through addition of some energy storage. Other reasons for hybridization include the cost, weight and volume of fuel cells relative to batteries, and the capture of regenerative brake energy. Some of these issues have been considered for 1500 kg sedans by Friedman (1999) and Friedman et al. (2000).

Sport utility vehicles have a relatively large potential for fuel economy improvements. This class of vehicle has some specific uses and drive cycles (such as towing) that may preclude the downsizing of the main energy converter to improve efficiency.

An ADVISOR simulation model based on validated component models is presented to investigate the potential of hybridization to improve fuel economy of a large sport utility vehicle. The objectives of this analysis are to understand the efficiency interactions of fuel cells and batteries, and determine if there is an optimal configuration.

VEHICLE DESCRIPTION

The large sport utility vehicle (SUV) chosen for this analysis is based on a 2000 four-wheel drive Chevrolet Suburban LT converted to a fuel cell hybrid electric vehicle (FCHEV). For the current modeling, the exterior geometry of the vehicle stays the same, and the conventional internal combustion engine drivetrain is replaced with a fuel cell/battery series hybrid electric drivetrain. The basic vehicle parameters for this class of vehicle are listed in Table 1 below.

Table 1 Large Fuel Cell Hybrid SUV Parameters

Drag Coefficient	0.45
Frontal Area, m^2	3.17
Rolling Resistance Coefficient	0.008
Mass, kg	2900

The total mass shown for the converted FCHEV is set 400 kg higher than the stock vehicle to approximate the increased weight of the fuel cell and battery components, and then held constant for the results given here. The fuel cell system on the vehicle is assumed to be supplied by a compressed hydrogen gas storage system. The present work does not consider the difficult packaging issues of fuel cell components.

Simplifying Assumptions for This Study

- *Previous work* with Virginia Tech. used the following simplifying assumptions:
  - Total mass of the vehicle was assumed to be constant regardless of the component sizes.
  - Component sizes varied in discrete steps.
  - Energy management strategy remained the same in all cases.
- *In this analysis* we have eliminated these assumptions except for:
  - Assumption that there will be no delay or fuel penalty associated with fuel cell system start-up and shutdown will remain intact
  - Instead, a fuel consumption penalty is included to account for inefficiencies during warm-up of the fuel cell system.

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Optimization Problem Definition

- Objective
  - Maximize fuel economy of fuel cell powered hybrid electric SUV
- Constraints
  - Performance equivalent to comparable conventional vehicle
    - 7 inequality constraints, such as accel., grade, SOC balanced…
- 8 Total Design Variables
  - 4 Component Characteristics
    - fuel cell peak power
    - traction motor peak power
    - number of battery modules
    - capacity of battery modules
  - 4 Control Strategy
    - low power fuel cell power cut-off
    - high power fuel cell power cut-off
    - minimum fuel cell off time
    - charge power set point

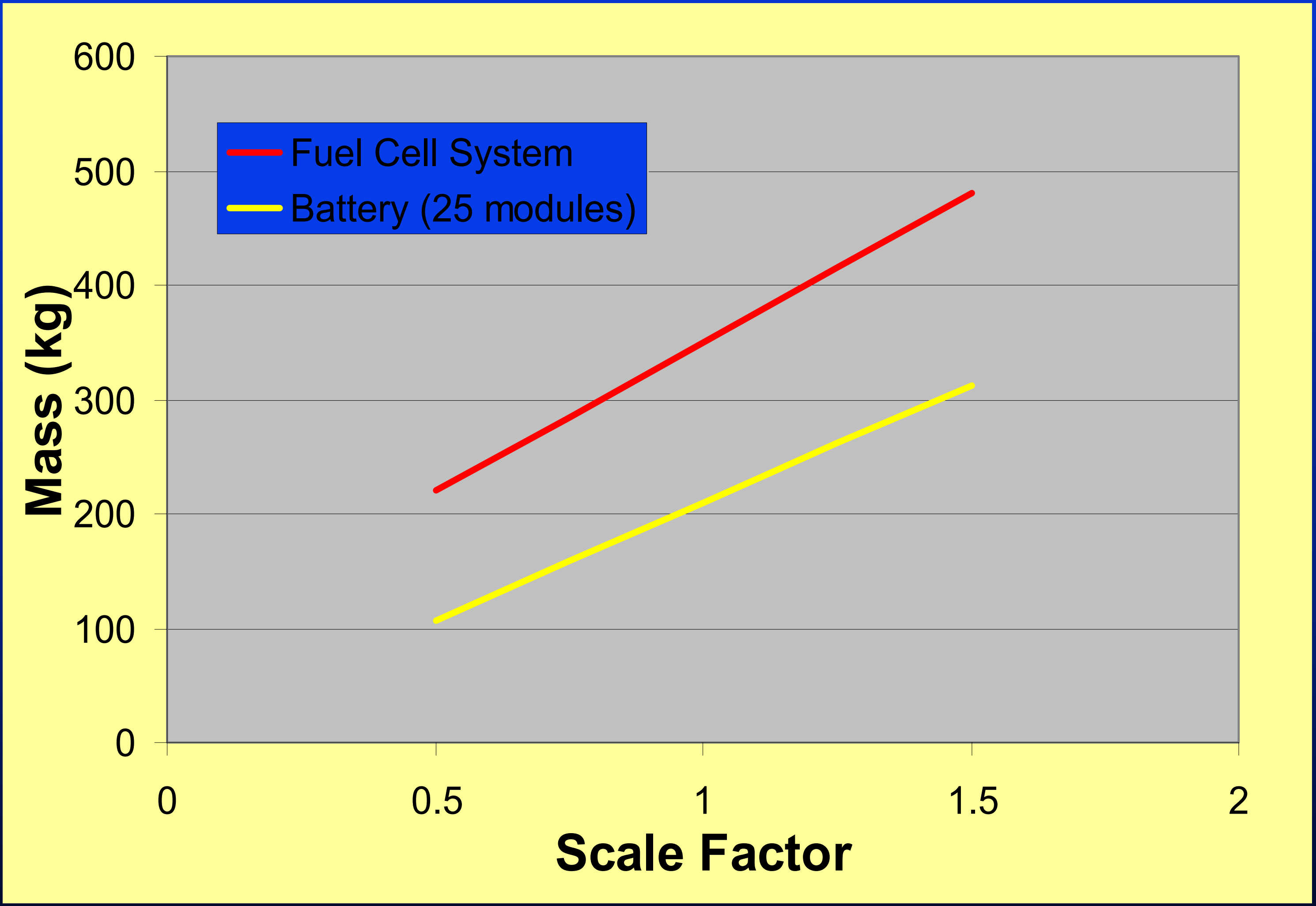
Vehicle Specifications

Vehicle Type	Rear wheel drive mid-size SUV (ie. Jeep Cherokee)
Baseline Conventional Vehicle Mass	1818 kg
HEV Glider Mass (No Powertrain)	1202 kg
Rolling Resistance	0.012
Wheel Radius	0.343 m
Frontal Area	2.66 m^2
Coefficient of Aerodynamic Drag	0.44

Baseline Components

Component	Description
Fuel Converter	Efficiency vs. net power performance data for 52 kW (net) Honeywell pressurized fuel cell system
Motor/Controller	AC induction motor developed by Virginia Power Technologies 83 kW @ 275 Vmin
Energy Storage System	Ovonic 45 Ah NiMH battery modules

Special Scaling Relationships Employed



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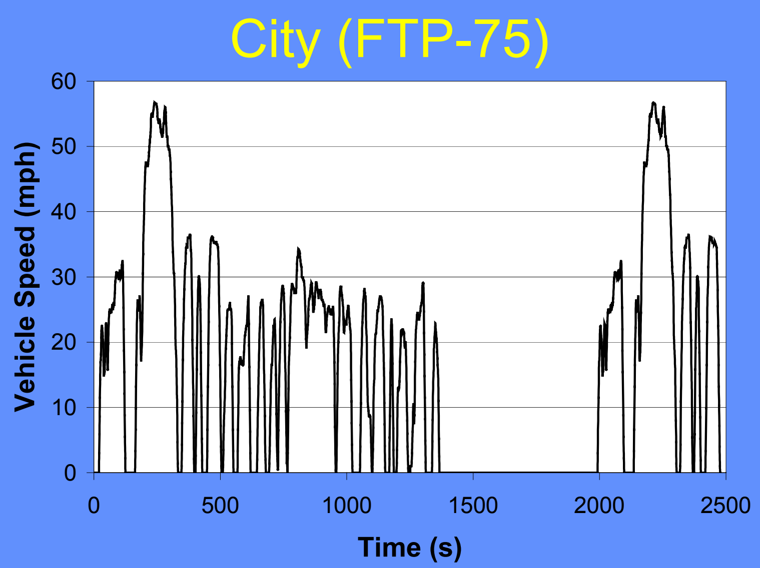
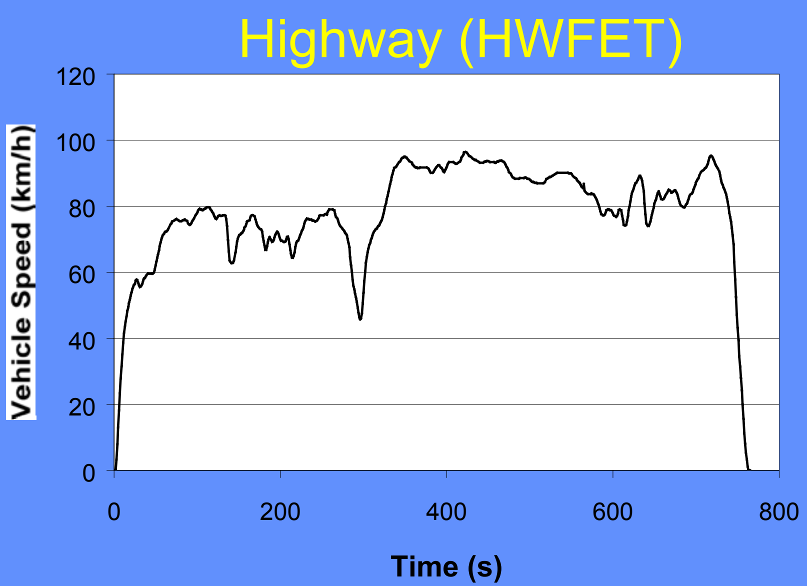
Results:
US City and Highway Cycles

- Single Combined US City and Highway Cycle Fuel Economy was the Objective Function

$$\text{Composite Fuel Economy} = \frac{1}{\left(\dfrac{0.55}{\text{City Fuel Economy}}\right) + \left(\dfrac{0.45}{\text{Highway Fuel Economy}}\right)}$$



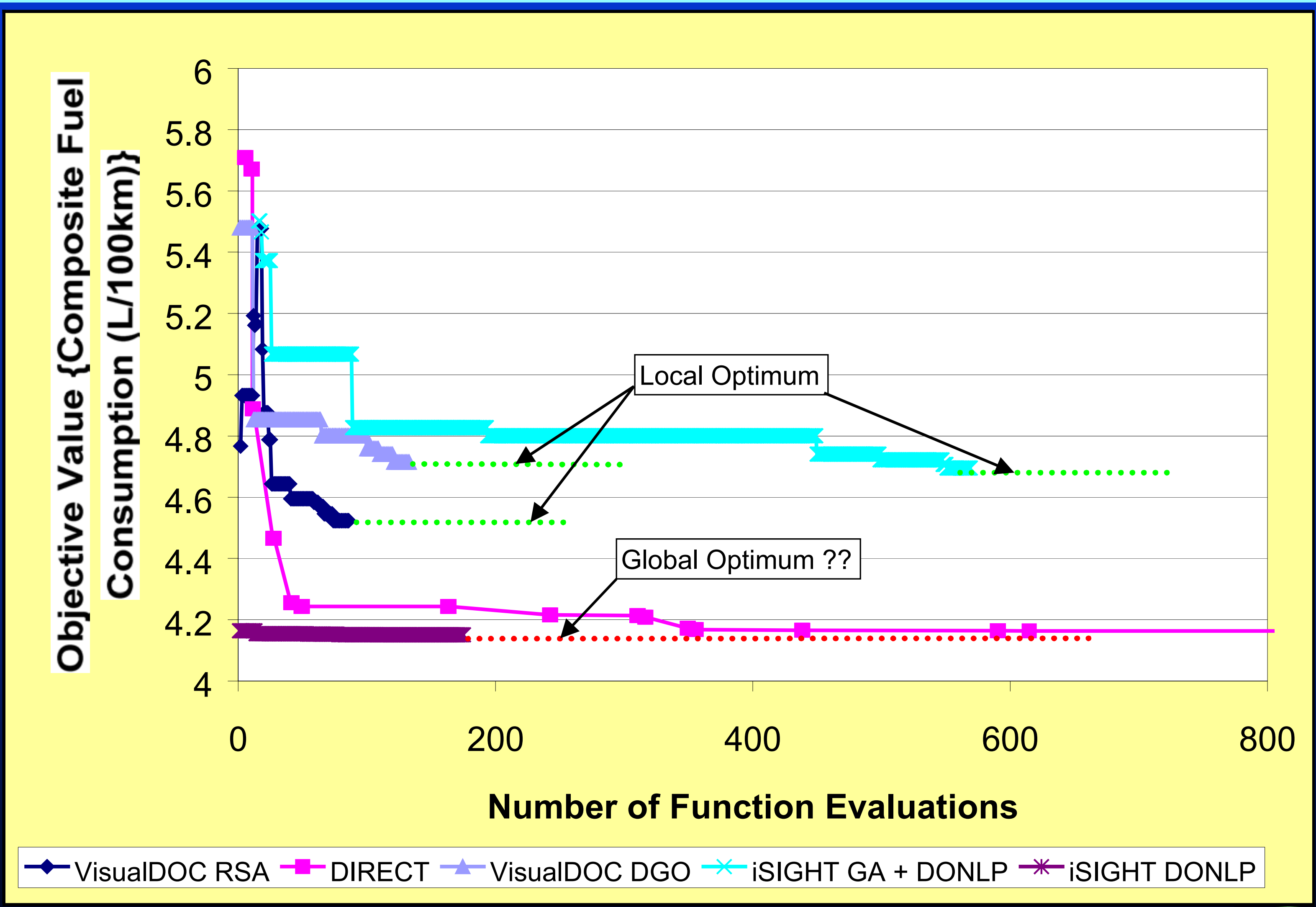


Optimization Results (combined city/hwy)

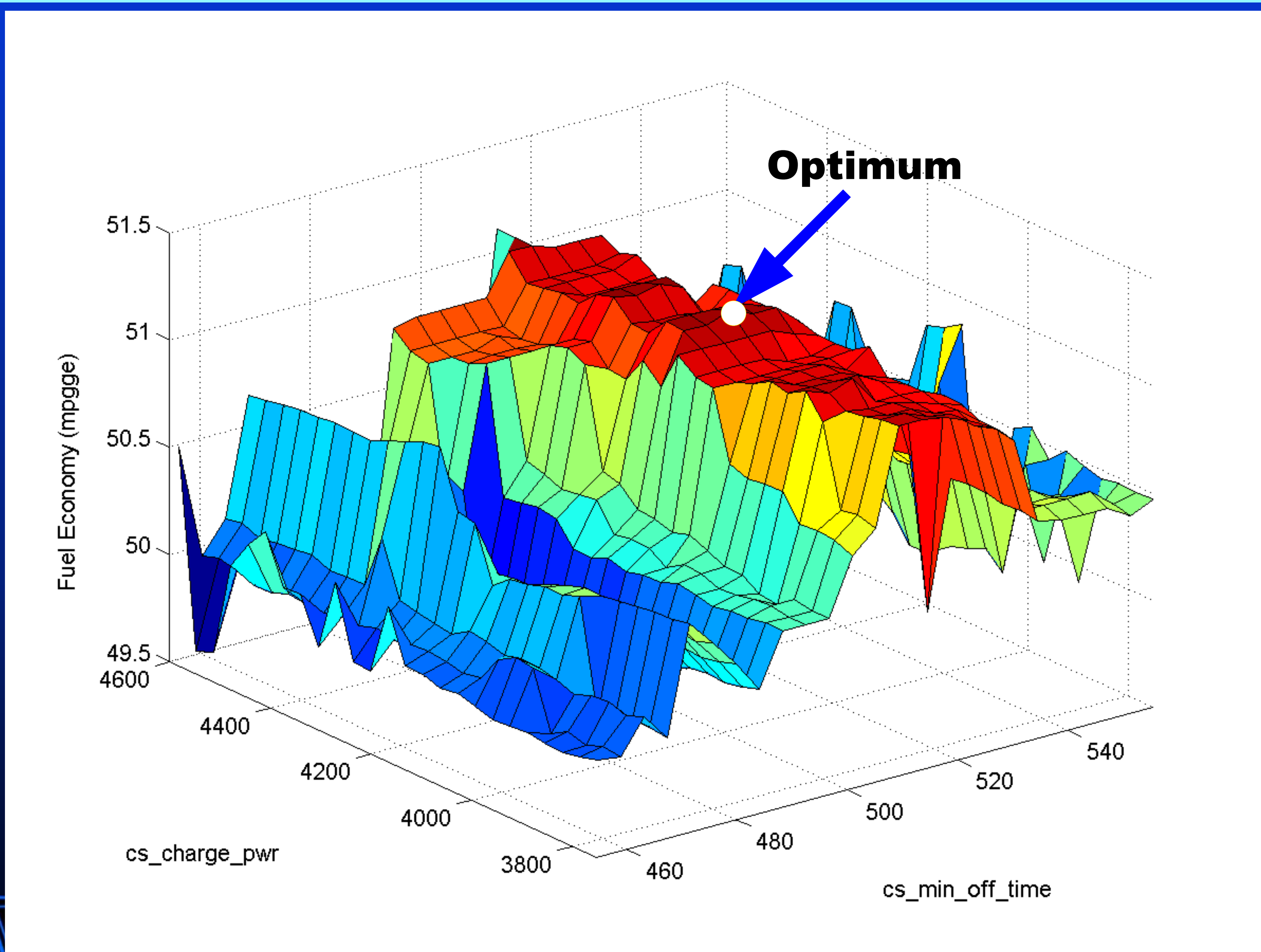
Function Evaluations	2641
Design Iterations	48
Elapsed Time	~111 hours
Initial Objective Value	5.654 L/100km (41.60 mgge)
Final Objective Value	4.163 L/100km (56.50 mpgge)

ADVISOR name	Description	Units	Initial Value	Final Value
fc_pwr_scale	Fuel Cell System Peak Power Scale	kW	104	66
mc_trq_scale	Motor/ Controller Peak Power Scale	kW	137	127
ess_module_num	Battery Pack Number of Modules	#	23	27.741
ess_cap_scale	Battery Module Maximum Ah Capacity Scale	Ah	52.5	48.8
cs_min_pwr	Minimum Power Setting	W	12500	20833
cs_max_pwr	Maximum Power Setting	W	37500	46451
cs_charge_pwr	Charge Power Setting	W	12500	13117
cs_min_off_time	Minimum Off Time Setting	s	505	187.2

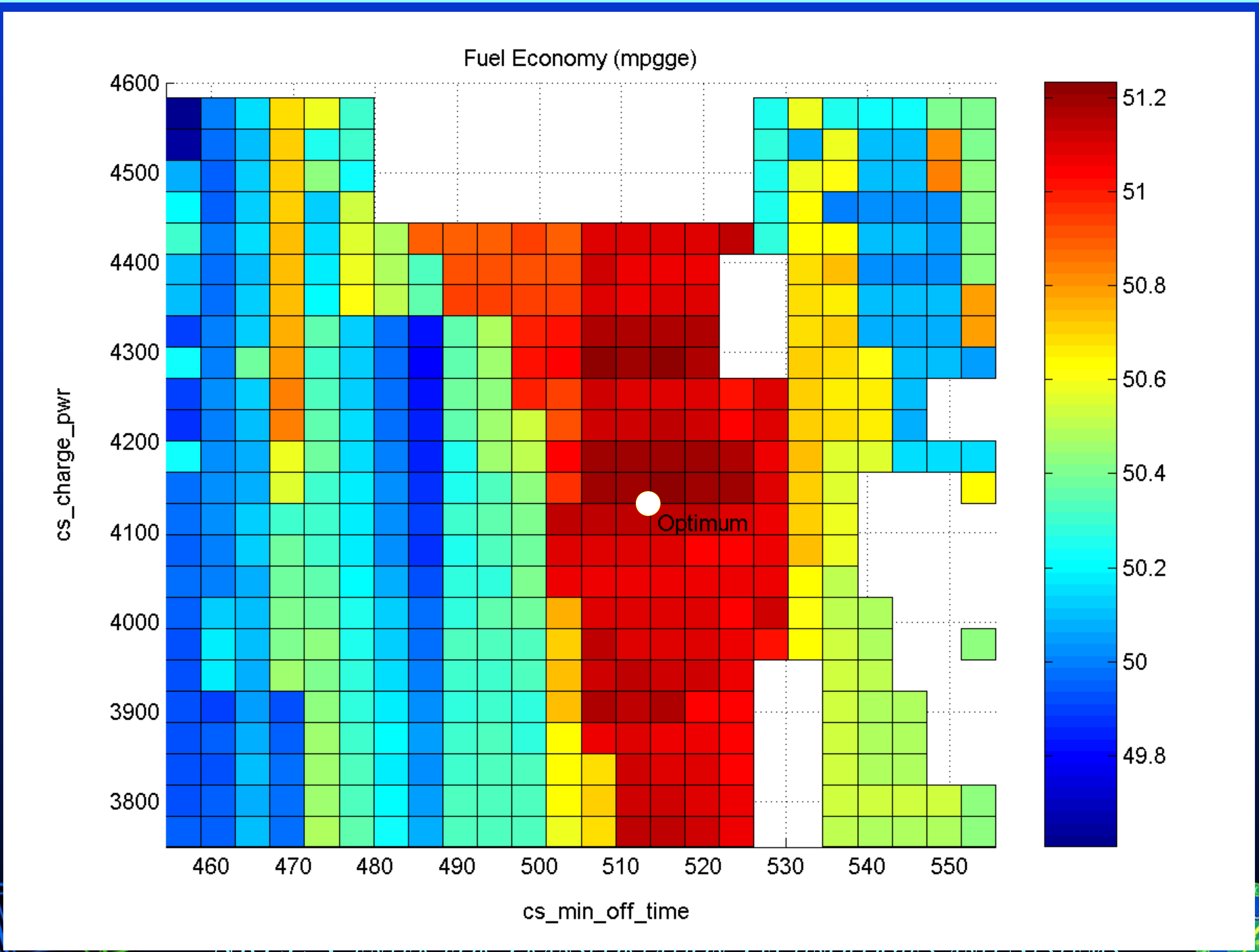
Fuel Consumption vs. Function Evaluations -- Only DIRECT Does Not Get 'Stuck'



2D Parameter Sweep - Fuel Economy Results

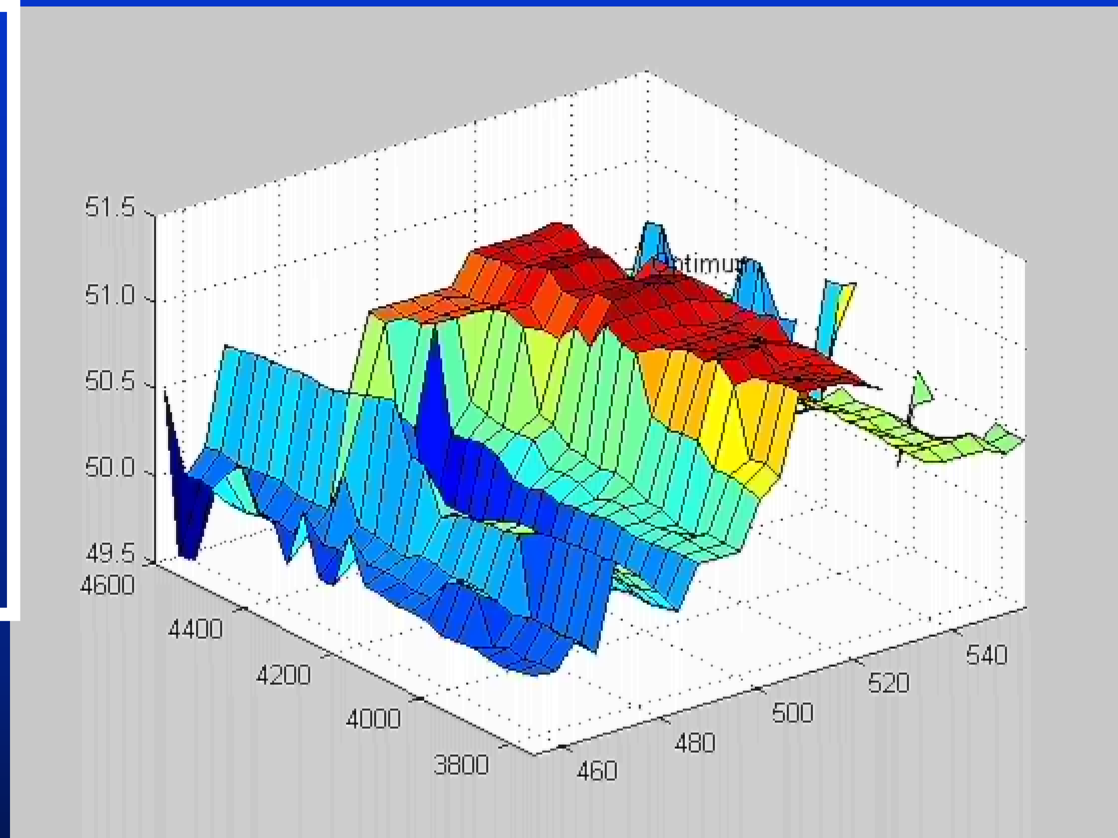


Fuel Economy in Feasible Regions



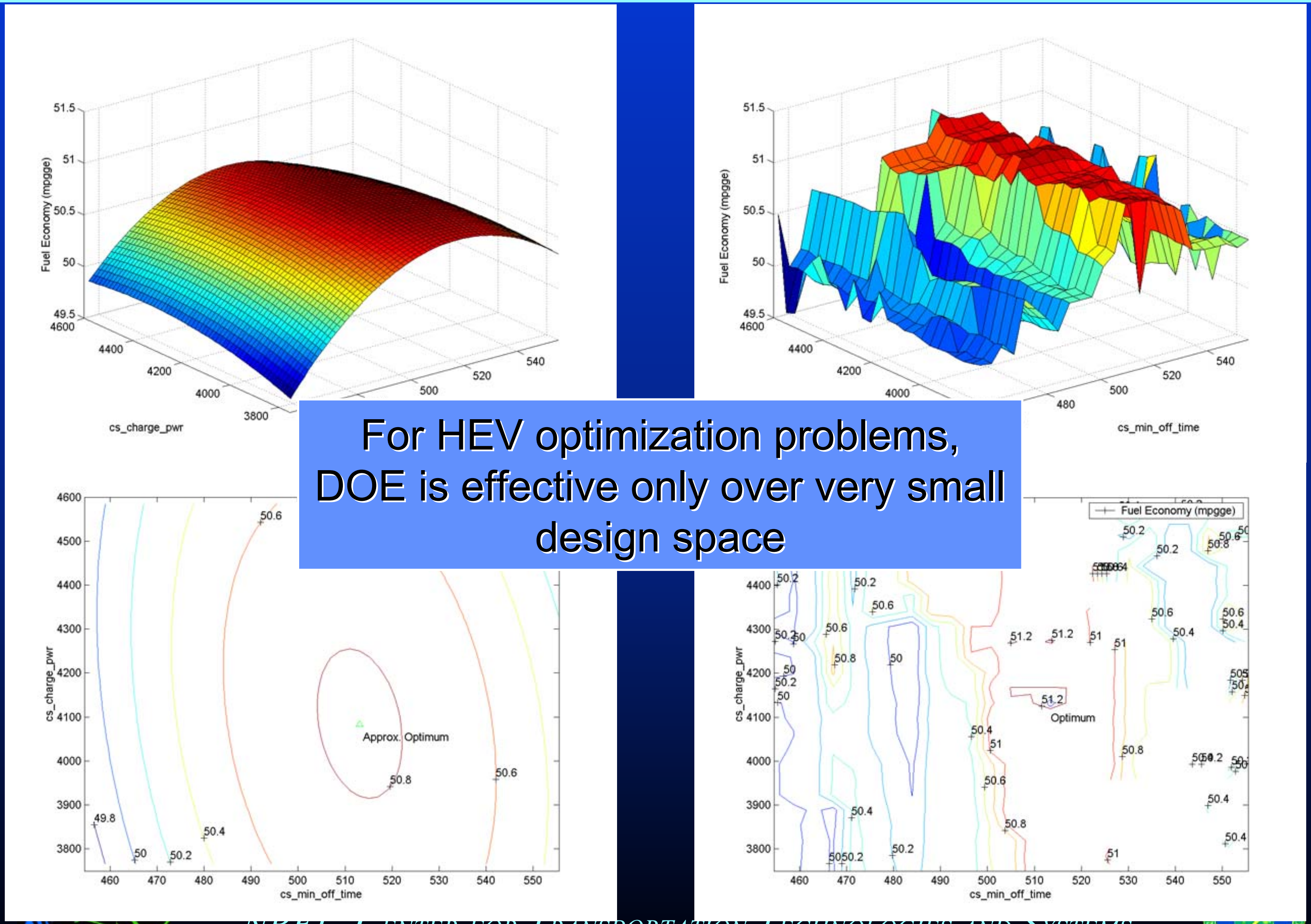
Complexity of the Design Space

Start animation by clicking on the graph, then click on the “arrow” button that will appear under the graph.



This only represents small portion (~1/25th) of 2 dimensions of an 8 dimensional space

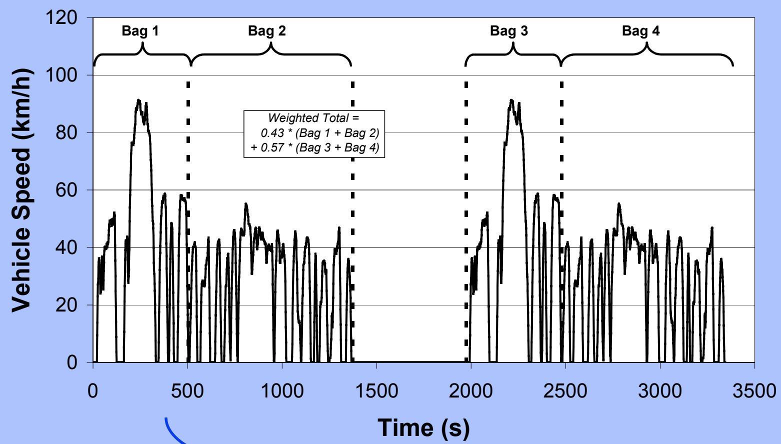
Design-of-Experiments 2nd Order Curve Fit vs. Actual Function Values

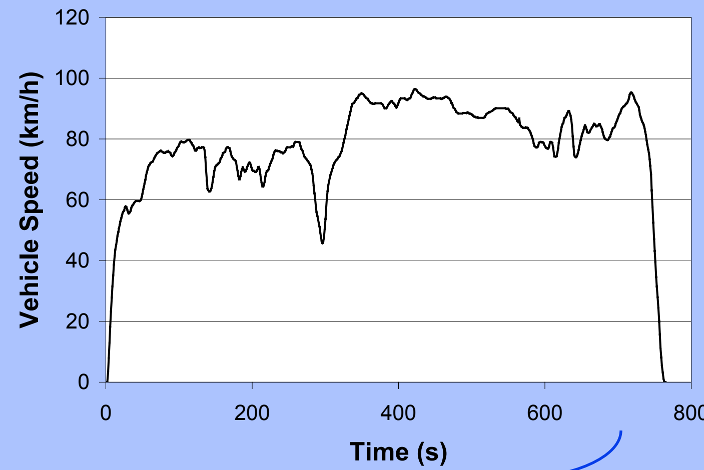


For HEV optimization problems, DOE is effective only over very small design space

Drive Cycle Variation

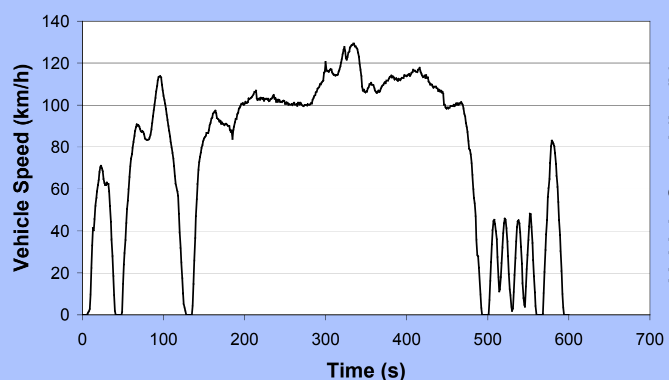
5 cycles Investigated (US city/highway are combined)



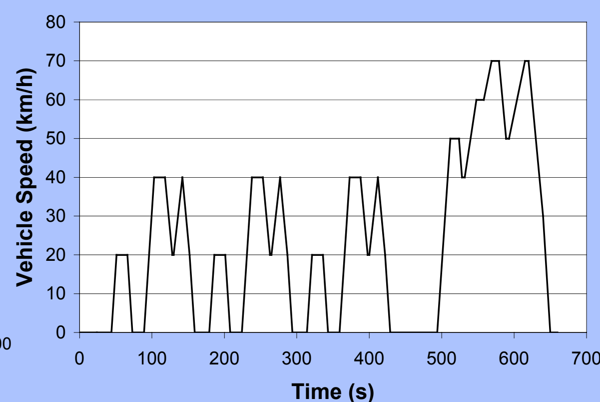


US city/highway combined cycle

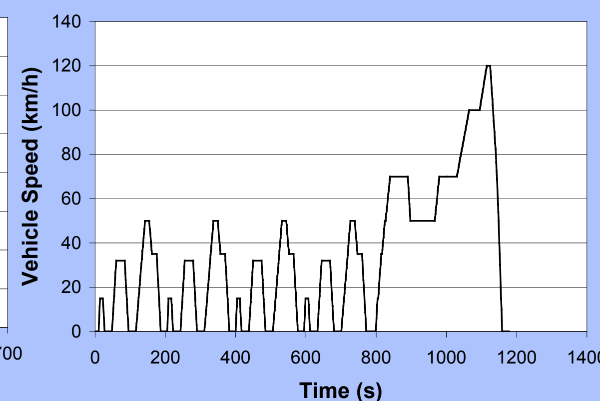
American US06



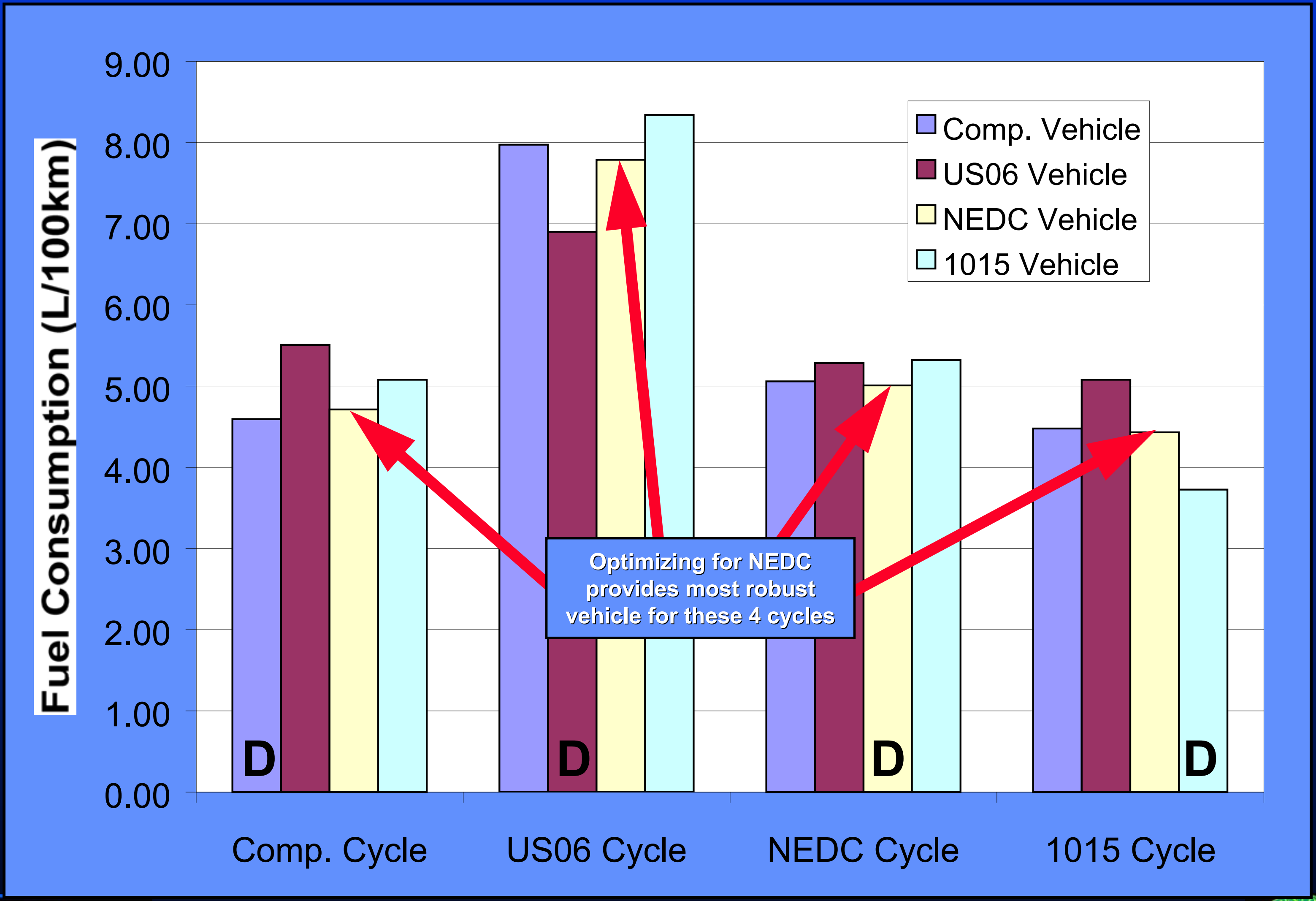
Japanese 10-15 mode



European NEDC



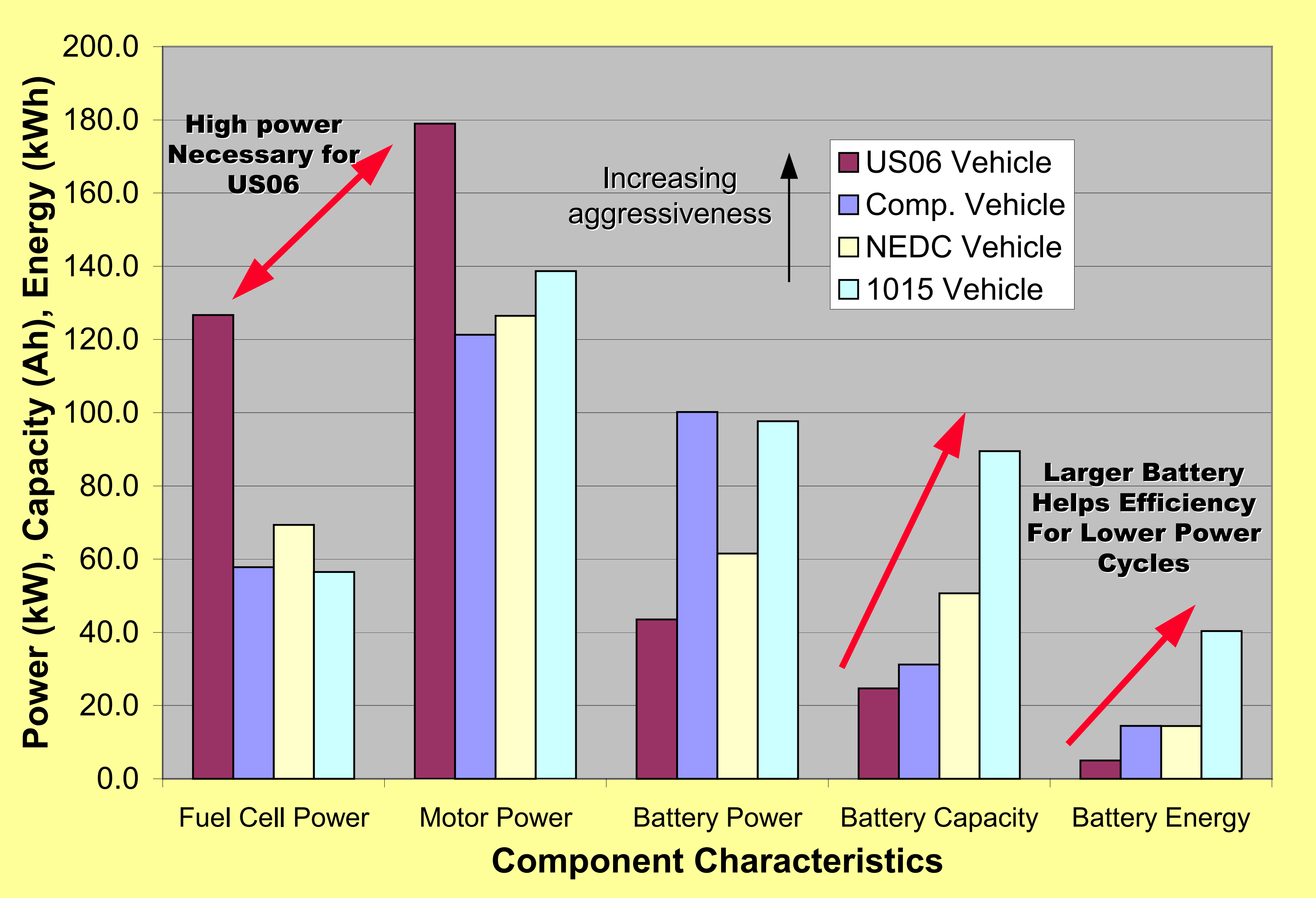
Results: Drive Cycle Investigation (D = vehicle designed for this cycle)



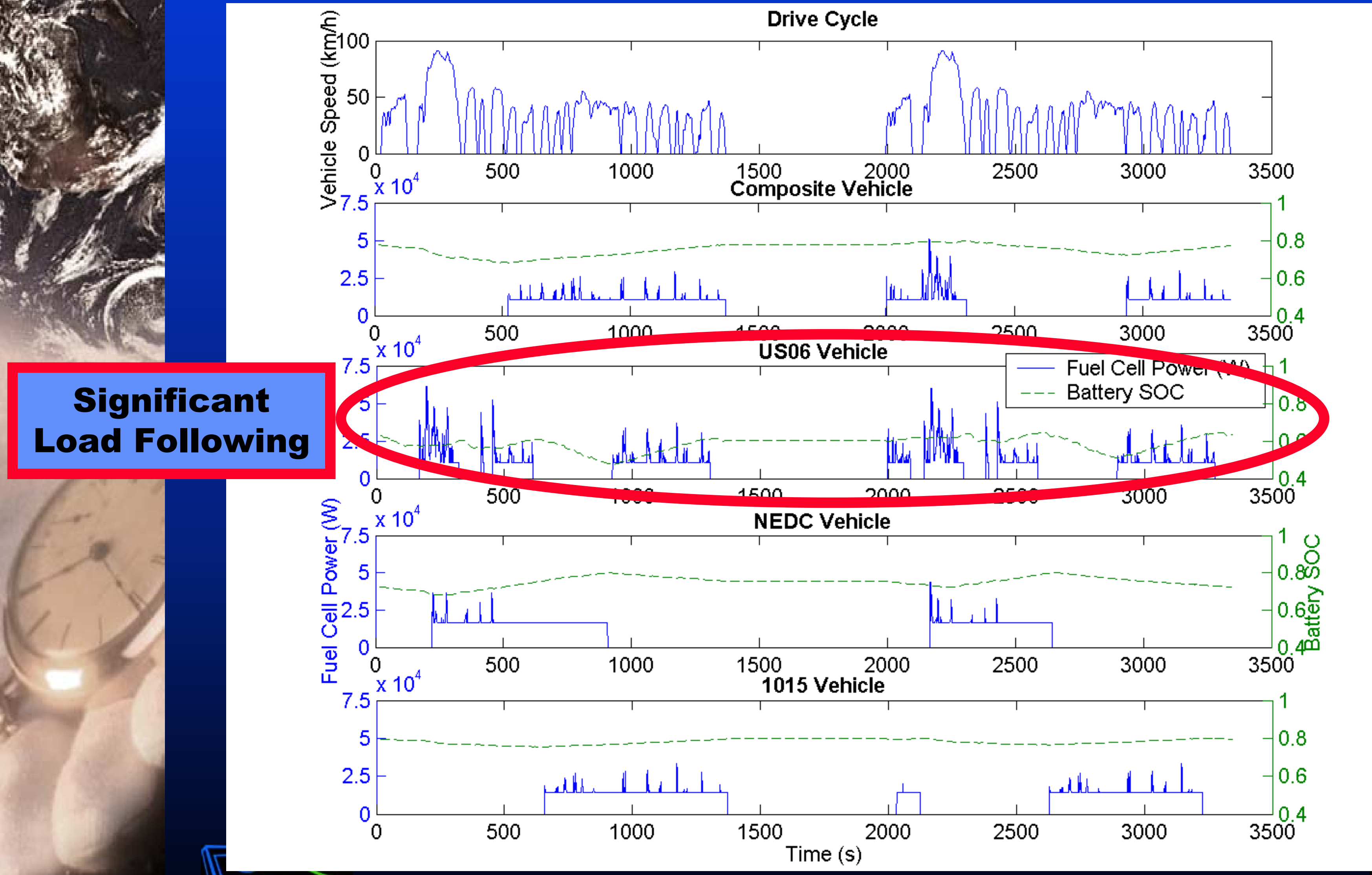
Results from Four Cycles -- Details

ADVISOR name	Description	Units	Comp. Vehicle	US06 Vehicle	NEDC Vehicle	10-15 Vehicle
fc_pwr_scale	Fuel Cell System Peak Power Scale	kW	57.8	127	69.3	56.5
mc_trq_scale	Motor/ Controller Peak Power Scale	kW	121	179	126.5	138.7
ess_module_num	Battery Pack Number of Modules	#	34.56	15	21.22	33.67
ess_cap_scale	Battery Module Maximum Ah Capacity Scale	Ah	31.2	24.7	50.6	89.5
cs_min_pwr	Minimum Power Setting	kW	10.8	10.4	16.7	14.6
cs_max_pwr	Maximum Power Setting	kW	55.0	82.1	55.8	49.8
cs_charge_pwr	Charge Power Setting	kW	5.6	10.4	25.3	5.4
cs_min_off_time	Minimum Off Time Setting	s	505	297.2	211.7	505

Characteristics of Components for Optimized Vehicles



Cycle Operating Characteristics on the 4 Cycles



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Conclusions

- ADVISOR is a robust "function call" for hybrid vehicle optimization
  - allows flexible numerical control of the SOC in the balancing iterations
- Derivative-free optimization algorithms appear to work best for HEVs with SOC 'noise'
- Drive cycle has a significant impact on fuel economy, hence optimal design
  - If 1 of the 5 cycles were to be selected as a good 'world' vehicle design cycle, the NEDC works well
- Optimization results indicate that an H_2 fuel cell system should be hybridized for efficiency, independent of start-up power requirements

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Future Work

- Link DIRECT with gradient-based optimizer to more efficiently search design space
- Explore options and benefits of enabling parallel analysis of the design space during optimization
  - Distributed computed on separate processors
- Improve fuel cell thermal models and analysis to investigate hybridization necessary to overcome start-up limitations